CHARACTERIZATION OF THE STRUCTURE AND SPECIES COMPOSITION OF URBAN TREES USING HIGH RESOLUTION AVIRIS DATA

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Introduction

Over 70% of the population in developed countries live in cities. World wide, the average urban population proportion is 42% (World population reference, 1993). Urbanization creates significant changes in land use and land cover, affecting the structure, pattern and function of the ecosystem. The public is increasingly concerned about how these changes influence our daily life and the sustainability of "quality of life" for future generations. The structure and function of urban ecosystems can be studied using the same methods as the study of natural environments.

Vegetation canopy, pavement, and buildings are the three important land cover types that affect the development of the urban ecosystem. The trees planted in urban settings along streets, in yards and parks are described as an urban forest, and they are an important part of the urban ecosystem. Urban trees play an important role in landscape beautification, in reduction of air pollution, and in moderating the urban energy budget, water use, and storm runoff. Increasing the proportion of pavement area during the process of urbanization strongly influences energy exchange, hydrology, and micro-climate (Arnold et al., 1996). Many problems facing management of the urban ecosystem are related to these factors. For example, urban heat island effects and increased storm runoff are related to the imperviousness of pavement and buildings. Air quality and water use are related to crown density and tree density. Air quality, energy partitioning, and hydrologic processes in the urban ecosystem depend on knowledge of tree species, leaf and stem surface areas, tree dimensions, percent of pavement cover, among other things. To understand how urban forests function and to estimate the value of their environmental services we must first recognize properties related to forest structure. Also, a good understanding of the structure of the urban forest provides information useful for urban managers, such as for planning tree pruning, leaf removal, and insect or disease control activities.

Basic information that is necessary to describe urban forest structure includes tree numbers, spatial distributions, species composition, dimensions, and growing conditions. Traditionally, this information is collected in field surveys. However, ground sampling is expensive and time consuming, and requires periodic updates to remain valid. Because of this the accuracy of potential information sources, e.g., from a city or regional tree database, is poor to uncertain. Aerial photo interpretation has been used successfully but is slow and expensive to conduct. The new high resolution spatial and spectral remote sensing technology brings us an opportunity to abstract spatially explicit urban forest information from remote sensing data. Also, it provides a mechanism for tracking / monitoring tree health and canopy cover changes through repeated data acquisition. With several new hyperspatial and hyperspectral digital imaging systems available on aircraft and soon, from space, we can investigate the use of high-resolution spectral data for characterizing and monitoring urban trees. In principle, images recorded by airborne or satellite-based sensors can be obtained at reasonable frequency intervals, at desired spatial and spectral resolution, and at lower cost per unit land area compared with traditional field survey methods (Martin et al., 1988; Ehlers, 1990). Remotely sensed data have been used for identifying and mapping vegetation, land use, and land cover in many regional or sub-regional assessments (Huang et al., 1995; Nowak et al., 1996; Morgan et al., 1993). However, estimation accuracy in urban settings becomes a problem due to the complex spatial assemblages of disparate patches. Urban areas are a mosaic of many tree types (e.g., species and dimensions), land uses, and man-made structures, each of which has different spectral reflectance characteristics (Gong et al., 1990). Unlike trees in rural forests, trees in the urban setting are often isolated. The influence of background, such as soil and shadow, makes the problem of characterizing trees by remote sensing even more difficult.

The unique optical sensor of AVIRIS delivers calibrated images of the upwelling spectral radiance in 224 contiguous spectral channels with wavelengths from 400 to 2500 nanometers (nm). Low altitude AVIRIS (Airborne Visible InfraRed Imaging Spectrometer) data were acquired at 4m spatial resolution, giving us an opportunity to study the urban forest at the single tree level. These enriched spatial and spectral data reduce the coarse resolution problems associated with broad-band low spatial resolution sensors. In boreal forests, Ustin et al. (1998), found that even at the same spatial resolution, the vegetation mapping accuracy is significantly improved using the hyperspectral 20 m AVIRIS data compared to 3-band 20 m SPOT data, especially for estimating dominant tree species.

Coupling GIS (Geographic Information System) to the analysis with remote sensing data will improve the accuracy of the results. Incorporation of spatial location has become a standard method for registering images to base maps, as shown in recent reports (Grimmond et al., 1994; Blackburn et al., 1997; Ambrosia et al., 1998; Lakshmi et al., 1998; Li, 1998; Shao et al., 1998). Our ability to accurately locate individual trees using the GIS database made abstraction of the spectral reflectance characters from AVIRIS data relatively easy. In this study, we demonstrate an important application of urban forest characterization by combining remote sensing and GIS techniques.

Objectives

There are three objectives for this study. The first objective is to identify urban tree species by physiognomic type, that is, whether they are broadleaf deciduous, broadleaf evergreen, or conifer types. The second objective is to identify urban tree structure, that is, the spatial distribution of trees, and their dimensions and growing conditions. Finally, we want to identify as many species as possible based on their canopy reflectance characteristics. Tree canopy information is important for urban planning and projects related to analyzing regional urban energy budgets, air pollution, and hydrology.

Methodology

Study site description

We selected the City of Modesto, California (latitude: 37°38'10" N, longitude: 121°11'10" W) as our study site (Figure 1). The city is located in the Central Valley of California and has a population of 186,000 with more than 70% of the population living in family households. City development began in the mid-1800's. Like many cities adjacent to the Sierra Nevada, it is undergoing a period of rapid population growth and expansion. Trees in Modesto are diverse in both species types and dimensions. There is a little topographic gradient in the study area or the surrounding region. The average elevation of the study area is about 11 m (35 ft.).

Data sets description

In order to investigate the use of imaging spectrometry for monitoring urban forests, two types of data sets were collected from the study area. High-spatial resolution AVIRIS data were acquired on the October 10, 1998. These data cover the main portion of the City. More than half of the 648 field measured trees in Modesto were covered by the AVIRIS flight pass. A GIS database includes information on all 75,629 street trees plus additional information on the 648 trees measured in the field.

Low altitude AVIRIS data. The low altitude AVIRIS imagery was obtained by a NOAA Twin Otter aircraft flying at an altitude of 3,810 m above sea level. As a result, these AVIRIS data have a spatial resolution of about 3.5 m for a sea-level target. The high-resolution flight navigation data (such as GPS) recorded during the AVIRIS overflight can be used during post-processing to correct for aircraft motion.

GIS Database. Four types of data were collected in the GIS database: base maps, street trees, land use, and soil. There are two street tree layers. The citywide street tree database contains 184 tree species and about 75,629 individual trees. Information for each tree includes: species code, scientific name and common name, tree ID number, year tree planted, and the access address (e.g. street address, city area, corner street, and corner address).

In Modesto, during the summer of 1998, 648 trees were measured. The random sample consisted of approximately 30 trees from each of the 22 most common species. Trees belonging to these 22 species account for over 90% of the entire street tree population. Field measurements included both tree dimension and maintenance information such as: DBH (diameter at breast height, or the diameter of the bole at about 1.5 m height), tree crown height, bole height at the bottom of the crown, crown diameter, total tree leaf surface area, geometric crown shape, site index, health/condition, and tree pruning rating. Based on these field measurements, a field sampled tree database was built for 22 species and total of 640 street trees. All field data were added to database for each of these trees.

Three-hundred-forty (340) trees that were measured in summer 1998 are included in the AVRIS flight data for this study. Figure 2 shows the spatial distribution of the field measured trees by tree type (e.g., broadleaf deciduous, broadleaf evergreen, and conifers), AVIRIS flight pass, as well as city area. Tree species and sample type distributions are shown in Figure 3. Broadleaf deciduous trees represent 81% of the sample population in the AVIRIS flight paths, and 93% of the total street tree population.

Spectral reflectance characteristic of trees

The unique spectral reflectance characteristic of vegetation, strong absorption in red wavelengths and strong reflectance in near-infrared wavelengths, allow us to separate vegetation from other ground surface cover. Differences in the allocation of foliage and stems and their architecture among tree species may provide sufficient information to uniquely identify them with the AVIRIS data. Such differences as leaf and branch zenith angles, leaf shape, internal anatomy, and leaf and branch surface roughness might cause at least some species, if not all of them, to have different reflectance spectra. Figure 4 shows the leaf spectra for six species that fell into three broad categories of tree types. As has often been observed in the past, in the infrared region, conifers have the lowest reflectance while broadleaf deciduous trees have the highest reflectance and broadleaf evergreen trees cover the middle range.

NDVI (Normalized Difference Vegetation Index), and red-edge, or other band ratio methods have been used for separating different amounts of vegetation. However, these simple ratio methods can not be used to identify tree species because they do not capture the unique features of specific tree conditions. The spectral reflectance characteristics of different tree species differ with the relative proportion of biochemicals, e.g., photosynthetic pigments, cell wall materials, water concentrations, and the scattering properties, affected by the internal leaf structures, and at the canopy scale, the three dimensional structure and distribution of stems and leaves of the trees. A common problem faced with this type of data is how to treat the mixed pixels that are common in analysis of isolated trees. SAM (Spectral Mixture Analysis) method in ENVI (Environment for Visualizing Images, Research Systems Inc., 1997), is based on the assumption that remotely sensed spectral reflectance is a linear summation of the different spectral properties at that specific location, allowing characterization of the ground surface cover at the sub-pixel level. SAM was used to identify the ground surface properties related to certain land cover types.

Procedures

Figure 5 shows the method and procedures followed in this study. Radiometric correction and georeferencing of the AVIRIS data was done to locate coordinates and allow overlaying of other GIS data layers in the database over the low altitude AVIRIS data. Using the GIS database that provides tree location, species, size, and leaf area, a spectral library is being constructed for each tree species and for different ground surface cover properties (such as pavement type, buildings, and land use). Based on this library, different spectral analyses were performed to obtain additional data layers that characterize tree type (i.e., broadleaf deciduous, broadleaf evergreen, and conifer) and additional layers that characterize different tree species. Accuracy analysis was done by comparing the results of the spectral analysis with known tree types in the GIS database.

AVIRIS data and spectral analysis

Atmospheric scattering and absorption effects within the image are corrected with a new modification of the Modtran code, using part of Robert Green's version of MODTRAN model for solar and atmospheric scattering. We are working on correcting the atmospheric scattering and absorption to retrieve surface reflectance but in the short time we had not obtained an acceptable calibration. Radiance was used for endmembers and for the analysis. Because the study site is small and flat, we assumed that all the spectral differences between pixels were due to the surface properties. Three bands of the AVIRIS data were georeferenced to overlay the GIS data. The street data layer in the GIS database was used for this geo-registration. By overlaying the tree layer in the GIS database with this geo-registered AVIRIS data, the location of different tree species was identified on the AVIRIS data. Not all of the field measured trees were selected for abstracting the spectral information to create the library. We identified criteria that must be satisfied before we used the information. For the site criteria, we focused on the tree crown dimensions and growing environment. The tree crown diameter must be wide enough to allow at least one pure tree-covered pixel. We used only isolated trees to avoid possible spectral mixing from different species. Twenty-two species from the field sampled GIS database were selected. Using their locations we were able to extract spectral reflectance for different tree species and for different surface cover properties. ENVI (Environment for Visualizing Images, Research Systems Inc., 1997) was used in abstracting spectral reflectance and performing spectral analysis. After we had obtained the spectral library for each tree species and different ground surface cover properties, we used linear spectral analysis to create the layered information for each tree type and species.

Results

Except for specific unique responses related to canopy health and growing conditions, the spectral reflectance differences of different tree species are controlled by their pigment, internal leaf structure, and water concentration, as well as tree architecture. Figure 6 shows the spectral radiance for three different tree species that represent three different tree types from this AVIRIS database. Japanese black pine (*Pinus thunbergii*), a conifer, has lowest reflectance at all wavelengths due to the small intercellular air space inside the leaf and its needle shape. Raywood ash (*Fraxinus angustifolia* 'Raywood') and camphor (*Cinnamomum camphora*) are broadleaf deciduous and broadleaf evergreen trees, respectively. Raywood ash has a higher spectral radiance than camphor in the visible and infrared regions due to the difference in pigment and water concentrations of these species. This suggests that we can identify the trees at least to general tree types in the urban forest using AVIRIS data. In the spectral library based on the AVIRIS data, broadleaf deciduous tree species were found to have higher spectral reflectance than broadleaf evergreen trees. Spectral reflectance for several broadleaf deciduous species is shown in Figure 7 for Modesto ash (*Fraxinus velutina* 'Modesto'), Bradford pear (*Pyrus calleryana* 'Bradford'), gingko (*Ginkgo biloba*), zelkova (*Zelkova serrata*), Moraine ash (*Fraxinus holotricha* 'Moraine'), and goldenrain (*Koelreuteria paniculata*). From this figure we can see that the spectral radiance of these species not only varies in magnitude but also in shape. Among these species, Modesto ash has highest radiance in the near-infrared region. But in the visible region, it has less radiance than gingko and Bradford pear. At most wavelengths, goldenrain tree has lowest radiance but at 1300nm region, its radiance was higher than the gingko. This indicates that we can separate these tree species by spectral analysis of AVIRIS data

We separated the land surface cover into different types, such as bare soil, pavement, building, water, and vegetation. Vegetation was further divided into grass, broadleaf deciduous, broadleaf evergreen, and conifer. Figure 8 shows the spectral radiance for these endmembers which are used in SAM or unmixing spectral analysis programs. In this study, we focus on tree characterization so that the results are presented in terms of tree types and tree species. Figure 9a shows the original AVIRIS false color image (R=850nm, G=650nm, B=550nm). Both the tree and land use patterns are clearly shown on this image. The broadleaf deciduous endmember layer from SAM (Figure 9b) shows where this tree type is located. The white color shows the highest fractional coverage for this tree type. This type of information was obtained for the broadleaf evergreen (Figure 9c) and conifer layers (Figure 9d).

Conclusions and Discussion

Our preliminary analyses demonstrate that isolated tree species can be identified and separated by type using high spatial resolution AVIRIS data. We used a GIS database to identify training sites and to validate the final maps. In addition to tree characterization, these data can be used for characterizing land cover. For example, we found that we can separate the man-made structures by the materials that are used, such as different types of buildings, houses, concrete and asphalt pavement. The potential value of these data for urban applications includes estimating tree health (e.g., evidence for stress) and leaf area for different tree species and site conditions. AVIRIS data acquired in spring or summer rather than October might provide better separation of some species or additional information about tree condition. For example, data acquired in both summer and winter seasons could be used to easily identify where the deciduous and evergreen trees are located.

Acknowledgment

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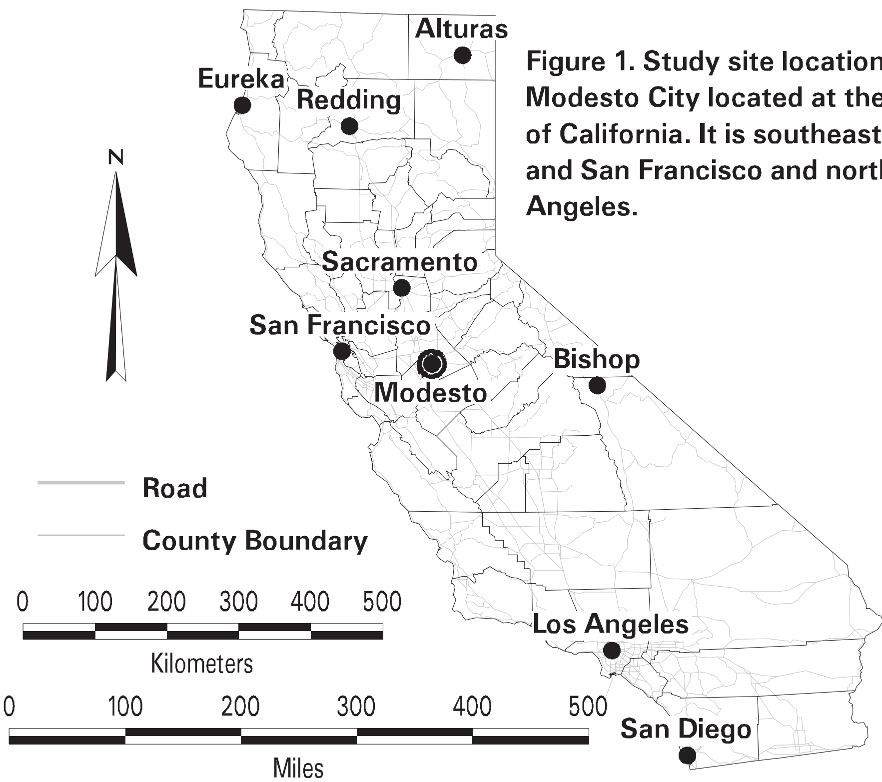


Figure 1. Study site location.
Modesto City located at the Central Valley of California. It is southeast of Sacramento and San Francisco and northwest of Los Angeles.

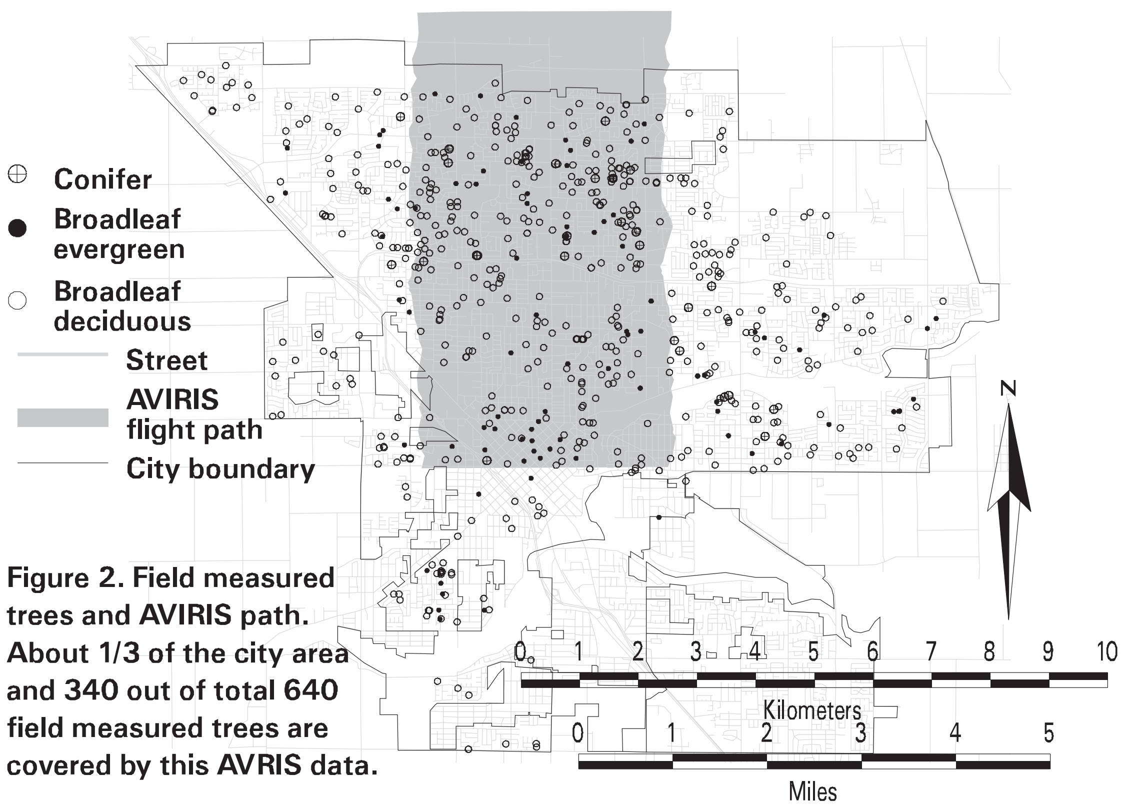


Figure 2. Field measured trees and AVIRIS path. About 1/3 of the city area and 340 out of total 640 field measured trees are covered by this AVRIS data.

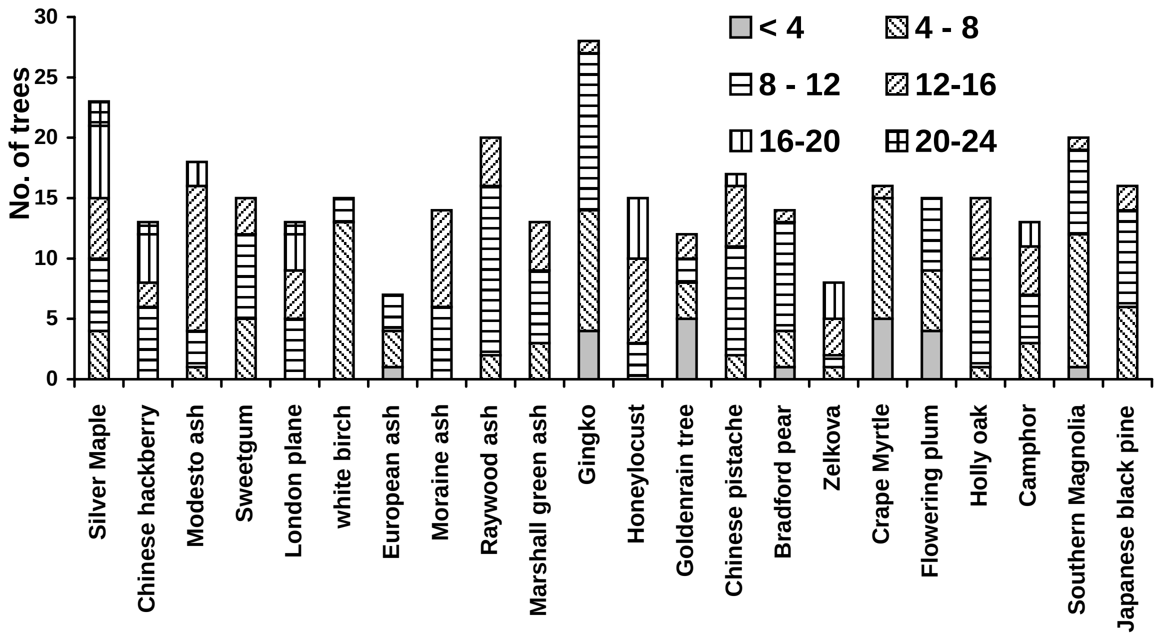


Figure 3. Species distribution of field mesured trees. Species commom names are shown on horizontal axis and the number of trees for each species are shown on vertical axis. Trees are subdivided into different crown diameter ranges as shown in the figure legend.

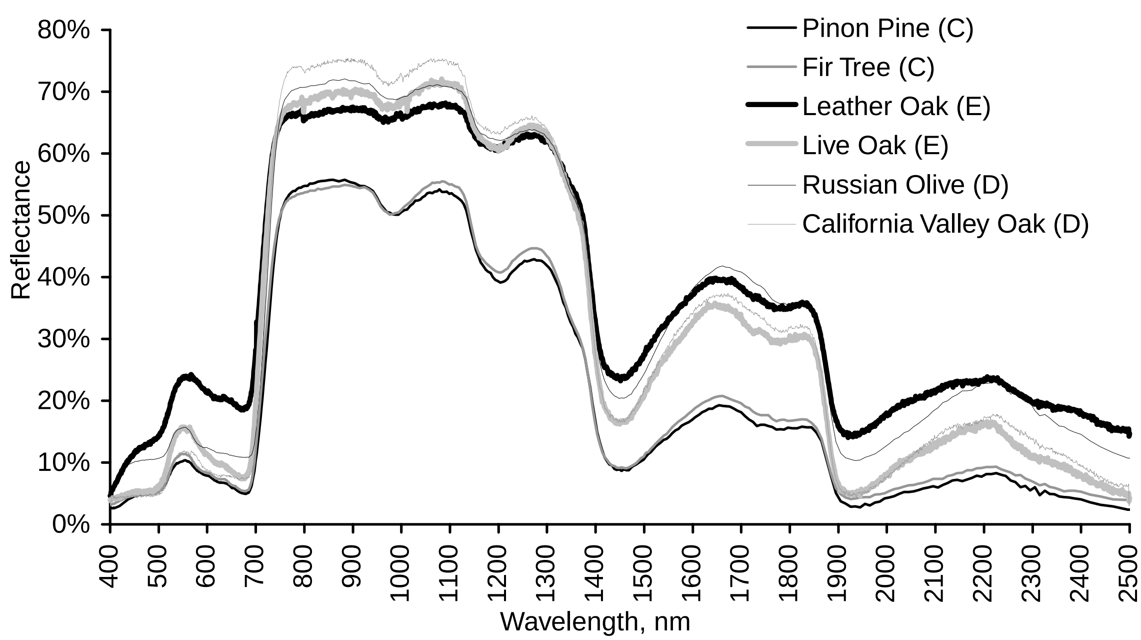


Figure 4. Leaf spectral reflectance of different tree species. Leters (e.g. C, E, and D) in the parentheses indicates the tree is a conifer, broadleaf evergreen, or a broadleaf deciduous tree. From the spectral reflectance we see that conifer trees are separated from broadleaf trees. In near infrared wavelength region the deciduous trees have higher reflectance than these evergreens.

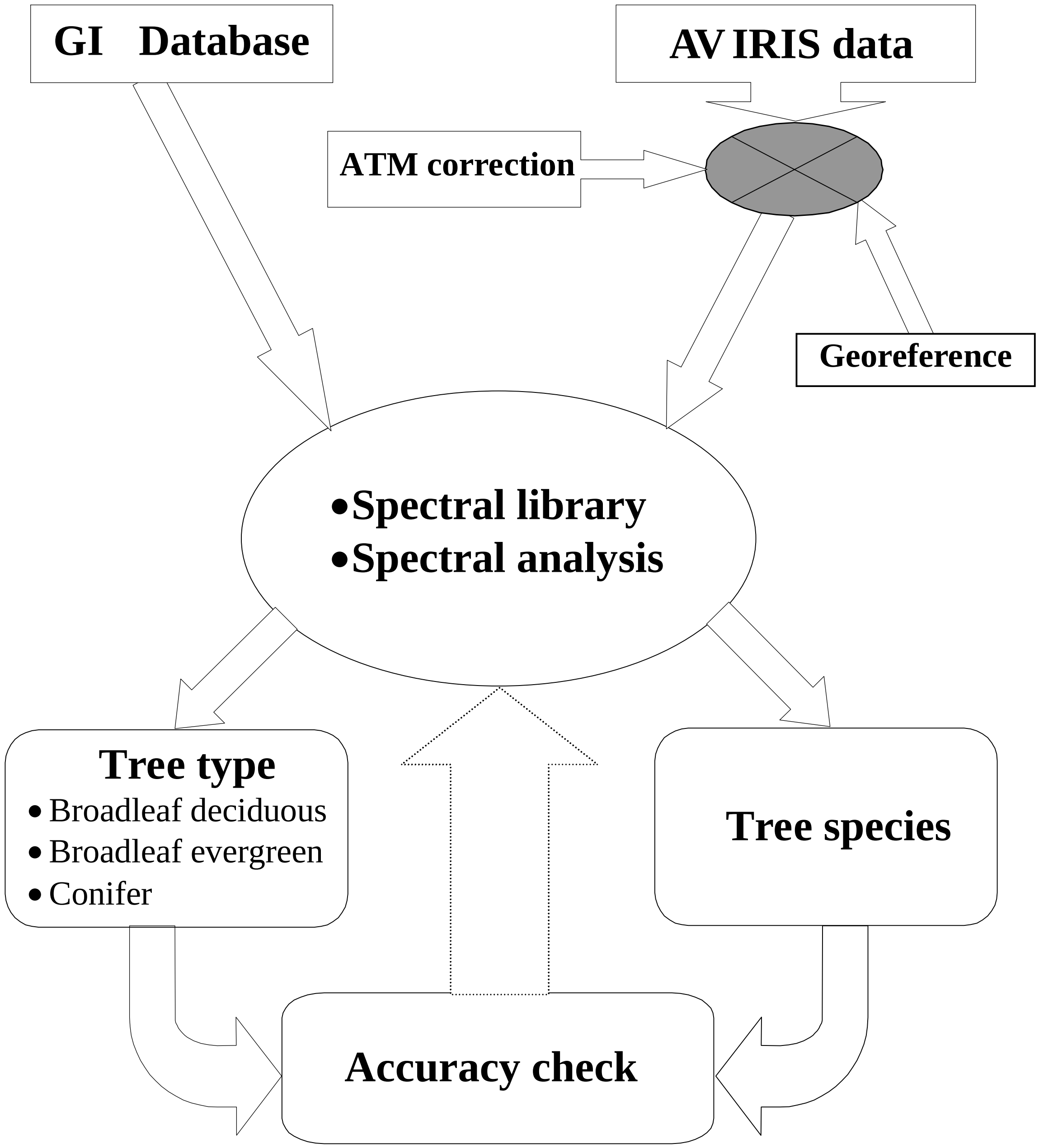


Figure 5. A schematic description of the urban forest tree characterization procedure.

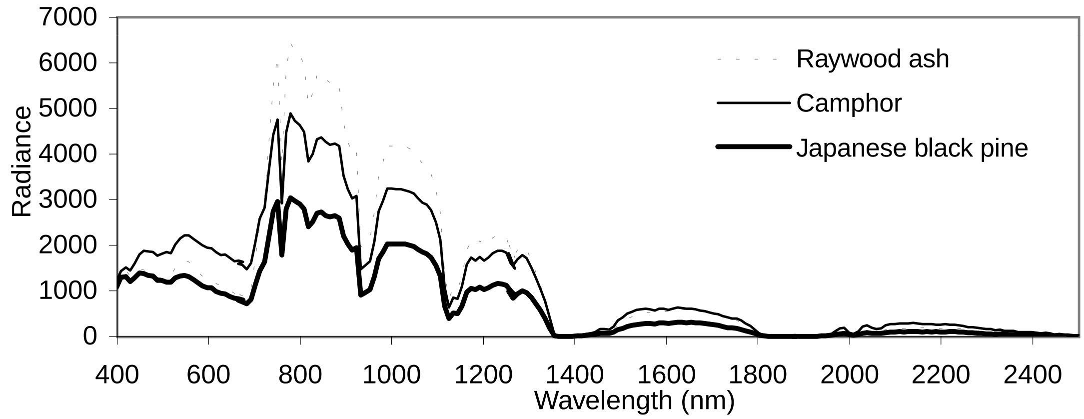


Figure 6. Radiance of three tree types. Japanese black pine (conifer) has lowest radiance. Raywood (broadleaf deciduous) has highest radiance in the infrared region. Camphor (broadleaf evergreen) has radiance between the other two trees, but it has highest radiance in visible wavelength region.

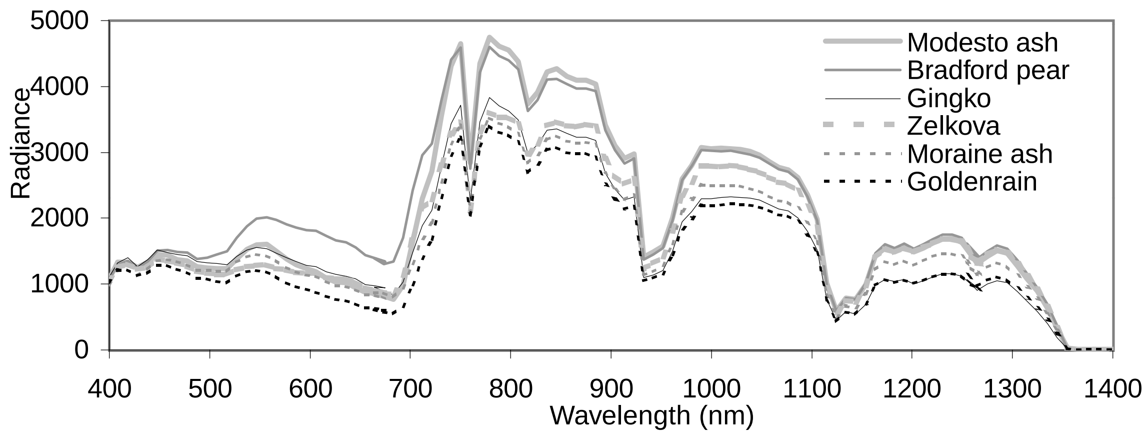


Figure 7. Radiance of different broadleaf deciduous tree species. Modesto ash and bradford pear have higher radiance in the infread wavelength region. Bradford pear has highest radiance in the visible region; Goldenrain has lowest radiance.

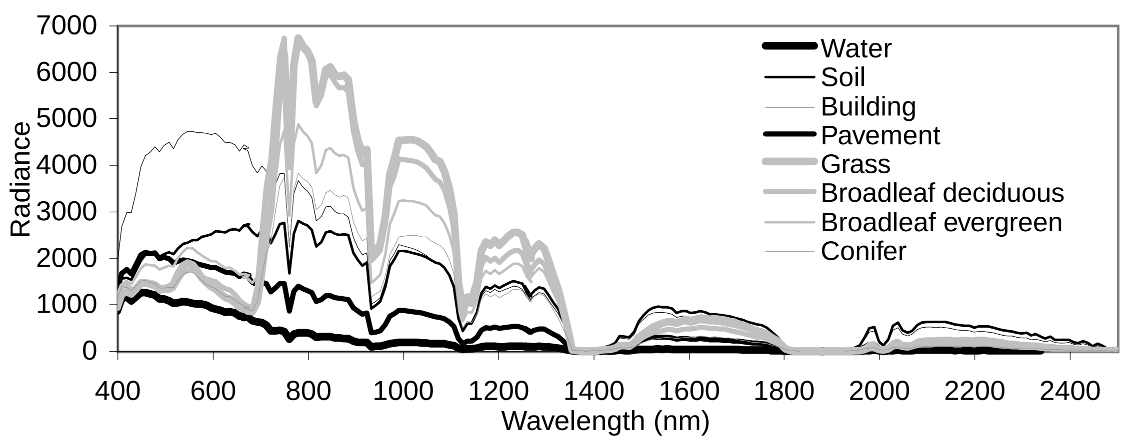
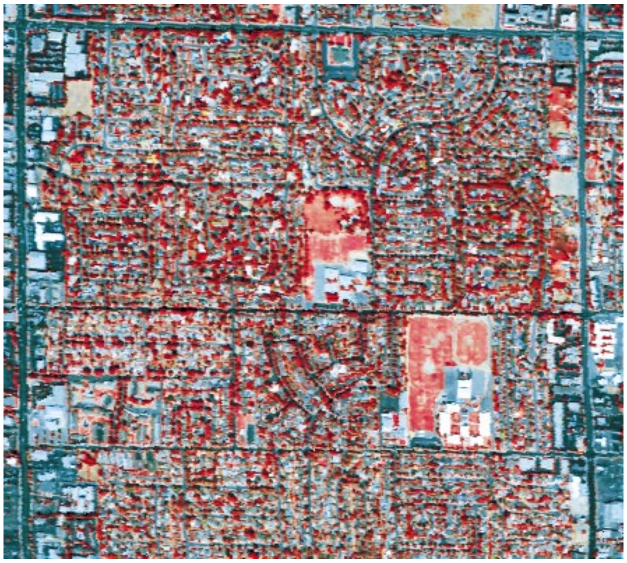
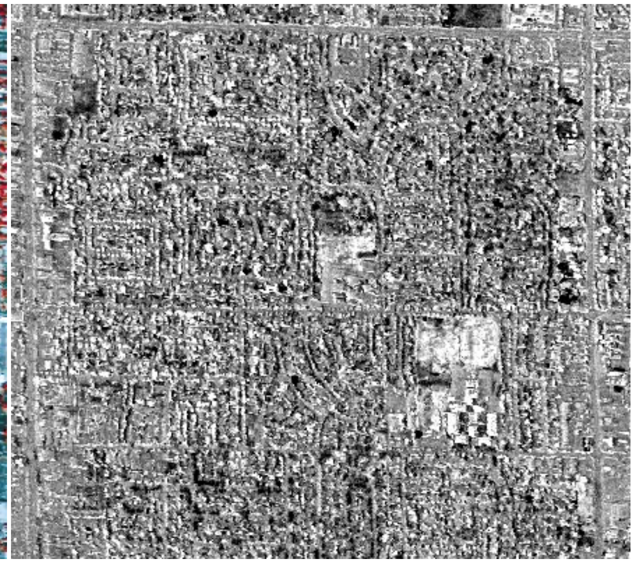
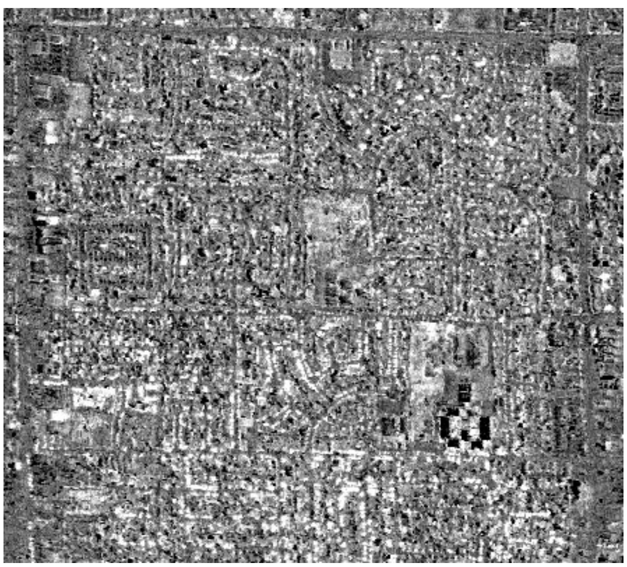


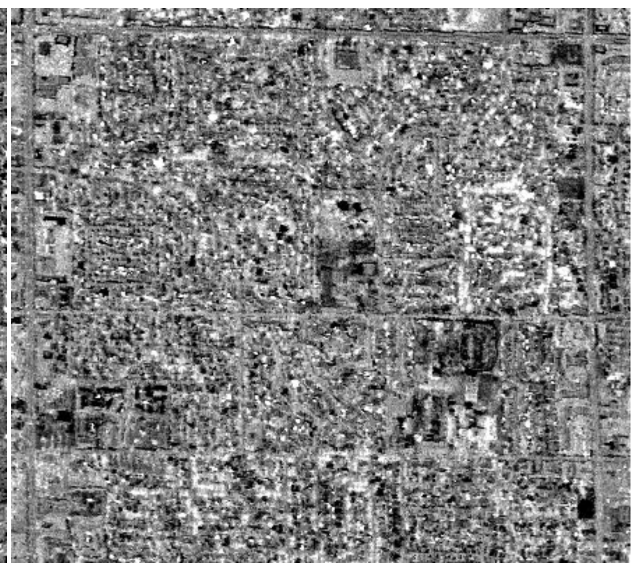
Figure 8. Radiance of endmembers. Radiance for eight endmemers are shown in this figure. The radiance of these ground properties not only varies with magnitude but also the spectral patterns are different.





a. AVIRIS (R=850,G=650,B=550) **b. Broadleaf deciduous**





c. Broadlead evergreen **d. Conifer**

Figure 9. Spectral analysis results.
Figure 9a shows the false-color image of regional AVIRIS data.
Figure 9b-d show the black-white endmember or fraction tree coverage for broadleaf deciduous, broadleaf evergreen, and conifer. In the black-white image, the bright color indicates higher fraction coverage.